Potential impacts of China's climate policies on energy security

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ABSTRACT

Energy security, as an indispensable constituent of economic security, has long been a top research priority, and the dynamics of energy security become particularly complicated with the involvement of climate change. In this work, we combined a one-sector integrated assessment framework with a series of well-proposed energy security metrics to extensively explore the unidirectional consistency between climate policy and energy security from the national perspective. Implementation of climate policy is generally beneficial for improving energy security. Specifically, climate policy helps to reduce the systematic risk of China's energy system according to the metrics of energy (oil) intensity, energy (oil) expenditures and per capita energy (oil) consumption independent of time scale options. As observed from the perspective of energy diversity, co-benefits arising from climate policy primarily emerge in the first half of this century, and they may gradually decline as emission constraints and the phasing out of fossil fuels are enhanced. Additionally, the macroeconomic costs required to reach China's committed carbon-peaking target might be far lower than the costs required to fulfill the emission budgets under the global 2-degree warming rise threshold. If the co-benefits of energy security are considered, the economics of climate policy is expected to significantly improve.

1. Introduction

As one of the core aspects of economic safety, energy security has long received considerable attention from both governments and scientific communities. Conventionally, security primarily refers to the security of supply (SOS), particularly oil supply (Alhajji, 2007; Gupta, 2008). As the fluctuation risk of energy prices increases, resources scarcity grows significantly, and the imbalance of energy supply and demand within and across regions is prominently enhanced, energy security is given a much richer and more extensive meaning that involves affordability, availability and accessibility (Kruyt et al., 2009).

The background of global climate change makes the issue of security more complicated: Climate change may worsen the spatial imbalance of energy supply and demand, and cause the conventional energy market to fluctuate more frequently and extensively, which would heavily increase the cost risks of the entire economic system. In addition, climate change affects the resilience of the energy system itself and energy-related infrastructures, which, in turn, makes the energy system more vulnerable (Farrell et al., 2006; Jewell et al., 2016). As a result, energy security further features its added acceptability, given the increasingly stringent situation of global warming (Sovacool and Brown, 2010). Here, acceptability should be better understood as the influences of

climate change on security risks.

On these grounds, the scientific communities always define the updated energy security as "low vulnerability of vital energy systems" (Jewell et al., 2013). Vital energy systems could be widely referred to the total primary energy supply system, or specific energy supply systems such as petroleum, nature gas and electricity. Geographic energy systems could also be included from the perspective of having specific global, national or sector boundaries (Cherp and Jewell, 2014). Regarding the vulnerability of energy systems, we primarily discuss the degree of risk exposure and the capacity of responding to risks (resilience) (Stirling, 1994; Jewell et al., 2013). Vulnerabilities also cover the disruptive risks of conventional energy fuels and the economic risks resulting from energy costs and market fluctuations (Greene, 2010). Consequently, both the traditional security risks and the low vulnerability of vital energy systems are considered to contribute to the long-term and dynamic assessment of future energy security with the intervention of climate change (Cherp and Jewell, 2014).

Traditional assessment methods are no longer suitable for studying the vulnerability of vital energy security. First, the conventional approaches are used to investigate supply risks of fossil fuels based on the historical and current energy market information. However, the status of fossil energy will undoubtedly decline. Thus, the emphasis on the so-

called vital energy system may largely be on future non-fossil energy. Particularly, the intensive involvement of primary renewables and second electricity will produce a new requirement for integrated system method of energy security assessment (Cherp and Jewell, 2014). Second, risks of global warming make the vital energy systems more vulnerable, and as regions with high climate sensitivities, climate change may significantly influence the affordability, availability and acceptability of energy services (Jewell et al., 2013). For example, the rise in global average temperatures intensifies the use of air-conditioners and other cooling facilities, which may bring new challenges to current power supply systems and increase the relevant energy costs of the economic system. Moreover, frequent and irregular heatwaves will also aggravate the contradiction between energy supply and demand within or across regions. Additionally, climate-related disasters can accelerate human-made energy capital depreciation and damage energy infrastructures, which may cause new-added energy security risks.

Consequently, research on long-term and dynamic interactions between climate policy and energy security based on integrated assessment models (IAMs) has aroused great concern. Bollen et al. (2009) discuss the potential relationships among climate change, local air pollution and energy security by employing the MERGE model, and stress that energy policy alone will not reduce global total oil demand, but rather delay its peak for a couple of years. For Europe, the considered climate policy mix may promote the attainment of its emission control goal and bring remarkable co-benefits such as the decrease of mortality associated with air pollution. Climate policies could lower the risks of vital energy security. First, climate policies are likely to reduce global energy trades, resource exploitation and energy imports of leading economies. Second, climate policies are beneficial for increasing the diversity of energy systems (Jewell et al., 2013). Take the US for example, the reach of the low-carbon target is heavily consistent with the diversity of power supply systems. Specifically, given the low-carbon goal, the supply of electricity becomes more diversified (Grubb et al., 2006). Climate policies help to decrease the cost competitiveness of conventional energy, accelerate the diffusion of non-fossil technologies and diversify the energy system (Schumacher, 2017), which contributes significantly to guaranteeing energy security (McCollum et al., 2013). Additionally, the positive impacts of climate policies include the decline of the total energy supply, decrease in the dependence on the energy mix and fossil fuels trade and growth in the gross domestic product (GDP) (Cherp et al., 2016). However, the influence of climate policies on energy security closely relates to the considered time scales. The potential benefits of climate policies primarily occur in the short- and medium-term, specifically before the first half of 21 century, while from the long run, these effects tend to decrease gradually until they become completely negative (Jewell et al., 2014; McCollum et al., 2014; Cherp et al., 2016).

The relationships between climate change and energy security are not bidirectional. The intense control of emissions could largely reduce energy imports, i.e., the implementation of climate policies brings the co-benefits of security (McCollum et al., 2011). Meanwhile, energy policies alone, such as the proactive control of energy imports for reaching energy independence, play a negligible role in emission reduction, not to mention the achievement of the global 2-degree warming-limit target (McCollum et al., 2014; Jewell et al., 2016). Thus, the insignificant climate co-benefits could not provide supportive evidence for political advocates to introduce intended energy independence policies. Additionally, much attention is also paid to the cost analysis of specific climate and energy policies. Based on the GCAM model, Iyer et al. (2015) studied the possible paths of the abrupt transition of the global energy system and estimated the corresponding policy costs under the 2 °C temperature-stabilizing target. These authors note that it is unwise to delay climate actions due to the remarkably positive impacts of short-term energy restructuring and mitigation behaviors on the attainment of energy security and climate targets, as well as on the relevant policy costs. Indeed, it is prominently cost-saving to

consider the goals of climate change, energy security and local air pollution simultaneously. The corresponding policy costs are much lower than the sum of the separated costs that would be incurred to achieve the different targets in isolation (McCollum et al., 2011; Jewell et al., 2016). More specifically, if the co-benefits associated with climate policies are fully considered, the cumulative policy costs would decrease by 0.1–0.7% of the GDP in 2030 (i.e., 100–600 billion US dollars) (McCollum et al., 2013).

Lessons learned from the existing studies reveal that there are unidirectional relationships between climate change and security, i.e., the implementation of climate policies brings considerable energy security co-benefits, particularly during the first half of this century (McCollum et al., 2011). From the literature analysis, we also found that the current relevant research primarily focuses on the global or regional scale, and little focus has been on the national level. This disparity if particularly true for developing countries such as China, which has been explicitly emphasized as one of the primary open questions of McCollum et al. (2014) and Cherp et al. (2016). The limitation of the conventional IAM framework may largely tell the story: the majority of the existing IAMs are global or multi-regional, which directly leads to the resulting focus of related research on interactions between climate policy and energy security (Jewell et al., 2014). Support at the country-scale for IAMs is, therefore, indispensable for us to extend the relevant study to the national level. As a result, our well-developed, one-sector energy-economy-environmental (3E) integrated model of China fits well within this requirement and allows us to investigate the possible interaction between China's climate policy and long-run energy security.

As the largest greenhouse gas (GHG) emitter and energy consumer, China is facing more overwhelming and pressing challenges in climate change and energy security than any other country, which enhances the high importance of studying the possible relations between China's climate policy and energy security. Theoretically, we first incorporated the possible emission budgets across various emission allocation principles under the 2-degree warming-limit target into a 3E-integrated model. Then, we developed a systematic simulation and analysis framework by examining a series of energy security metrics. Empirically, our emphasis is primarily on exploring the potential unidirectional consistency between climate change and energy security that has been found at the global level, i.e., investigating the dynamic long-term impacts of climate policies on security. Additionally, one of our research goals was to analyze the macroeconomic costs and energy security co-benefits of climate policies.

The remainder of this work is organized as follows: Section 2 includes the introduction of the model methods and involves brief descriptions of our 3E-integrated model and well-developed metrics of energy security. Section 3 designs the scenarios, i.e., introduces emission budgets according to representative emission allocation plans under the 2-degree temperature-limit threshold. The primary results and related analyses are provided in Section 4, and the last section summarizes our conclusions.

2. Methodologies

2.1. The basic integrated assessment model

The implementation of the entire empirical simulation, which includes the outputs of energy, economy and emissions, and the consideration of climate policies, primarily depended on the Chinese one-sector 3E-integrated assessment model, CE3METL. This model is a Chinese version of the global E3METL (**E**nergy-**E**conomy-**E**nvironmental **M**odel with **E**ndogenous **T**echnological change by employing **L**ogistic curves), which is lead-developed in 2013 by *H. duan*. This model features innovative multiple technological diffusion mechanisms, i.e., the policy-driven multi-logistic curves (Duan et al., 2013). With these new mechanisms at hand, we could better describe
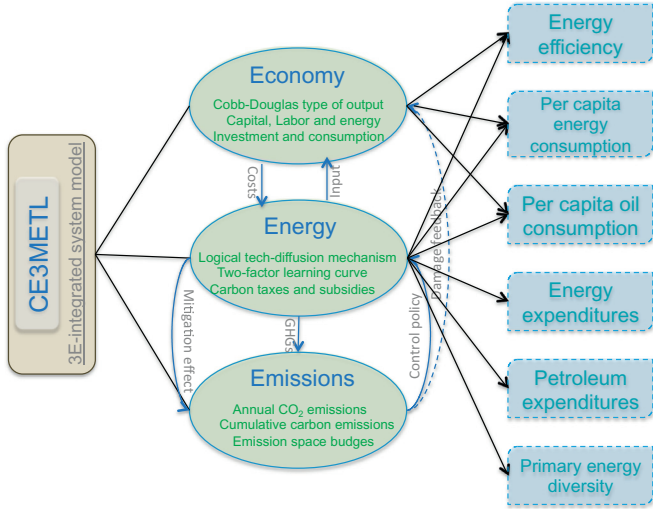
Fig. 1. Model framework and simulation roadmap.

multiple energy technologies in the targeted IAM using the original technological penetration rules and cost competitiveness, which contributes to portraying the long-term dynamic interactions among various technologies in the 3E complex system (Duan et al., 2015). In the current version, CE3METL incorporates three types of fossil fuels, i.e., coal, oil and natural gas, and seven categories of non-fossil technologies, which cover nuclear, hydro, geothermal, PV solar, wind, biomass and tide energy.

We have completed and published several works based on both E3METL and CE3METL that surround the thesis of cost analysis of climate policies, optimal policy options under given climate targets, possibility and path analysis on achieving national climate goals, cost-benefit of integrated assessment of power substitutions, and potential contribution to China's bilateral reduction on global warming-limit task (Duan and Fan, 2017). In this work, we continued to employ this model with the intention of examining the potential impacts of China's climate policies on energy security. The model framework and research roadmap are depicted in Fig. 1.

2.2. Evaluation system of energy security

With the simulation outputs of CE3METL, we needed to build an effective metric system to evaluate long-term security. The most representative indicators were well considered, and cover energy and oil intensity, per capita energy and oil consumption, energy and oil expenditures, and energy diversity (Kruyt et al., 2009).

Specifically, energy (oil) intensity is defined as the ratio of total primary energy (oil) consumption and the gross domestic production (GDP). Transparently, the higher the energy intensity, the lower the energy efficiency. Likewise, and the bigger the oil intensity, the higher the dependency of the economy on oil, and the more vulnerable the energy system. Per capita energy (oil) consumption is the proportion of energy (oil) consumption to the total population. Energy (oil) consumption in CE3METL is yielded using an endogenous optimization of key control variables, while the population is exogenously given in terms of World Bank projections (World Bank, 2015). It is easy to see that the energy system will become more vulnerable as the per capita energy or oil consumption grows. Energy (oil) expenditures are also effective metrics to examine the safety degree of the energy-economic system. Indeed, the higher the energy (oil) expenditures, the more vulnerable the key energy systems (Kruyt et al., 2009). In CE3METL, the oil expenditures are calculated by multiplying the oil consumption and the corresponding market price that represents the exploitation costs, the transportation and external environmental costs. The total

energy expenditures $TEC(t)$ are the sum of the energy composited prices multiplied by the total primary energy demand (TPED) weighted by the market share of each type of energy, that is

$$TEC(t) = \left(\sum_{i \in I} S_i(t) C_i^f(t)(1 + tax_i(t)) + \sum_{j \in J} S_j(t) C_j^{nf}(t) \right) E(t) \qquad (1)$$

where I and J are the sets of fossil and non-fossil energy technologies, respectively; $S_i(t)$ and $C_i^f(t)$ denote the market share and unit cost of fossil fuel i, respectively; and $C_j^{nf}(t)$ and $S_j(t)$ represent the unit cost and market share of non-fossil energy technology j, respectively. Regardless, $E(t)$ yields the TPED and the environmental external costs of fossil fuel i are measured by the carbon tax $tax_i(t)$.

The evolutionary relations among the various technologies are mostly governed by the differences in cost competitiveness, which is described by the policy-driven multi-logistic curves. In general, coal is chosen as the marker technology in CE3METL, and the underlying relationships between any couple of technologies could be portrayed by the relative relations between one of the targeted technologies and the marker, which is then contingent on the relative costs (Duan et al., 2015). To be specific, we denote $C_{coal}(t)$ and $C_k(t)$ as the unit cost of coal and any energy technology k. Then, the relationships between technology k and coal can be described by

$$\frac{dS_k(t)}{dP_k(t)} = \omega_k S_k(t) \left(\overline{S}_k \left(1 - \sum_{\tau \neq k} S_\tau(t) \right) - S_k(t) \right) \qquad (2)$$

where ω_k represents the substitution capability parameter, $\overline{S}_k$ is the possible maximum of market potential for technology k, and we have $0 \leq \overline{S}_k < 1$. $P_k(t)$ as the relative cost ratio of coal and technology k, i.e.,

$$P_k(t) = \begin{cases} \frac{C_{coal}(t)(1 + tax_{coal}(t))}{C_k(t)(1 + tax_{k \neq Coal}(t))}, & k \in I \\ \frac{C_{coal}(t)(1 + tax_{coal}(t))}{C_k(t)(1 - sub_k(t))}, & k \in J \end{cases} \qquad (3)$$

where $sub_k(t)$ is the possible subsidy rate (ad valorem) for alternative technologies. Thus, the lower the cost of technology k, or the higher the cost of coal, or the stricter the carbon tax policy, the larger the relative cost rate, and the more competitive the technology k.

Another important indicator for measuring energy security is energy diversity, for which the Herfindahl-Hirschman Index (HHI) and Shannon-Weiner Index (SWDI) are the most representative metrics. The results for both HHI and SWDI are remarkably similar, and these indices can, therefore, be viewed as equivalent in most situations (Grubb et al., 2006; Kruyt et al., 2009). On these grounds, we chose the more common index, SWDI, to measure China's long-term energy diversity in this work. For any technology k, the given market share $S_k(t)$ and corresponding logarithm $lnS_k(t)$ such that $SWDI(t)$ is defined as follows:

$$SWDI(t) = - \sum_k S_k(t) \ln S_k(t) \qquad (4)$$

3. Scenarios design

The 2 °C warming-limit target (above pre-industrial levels) has been established as one of core tasks of the Paris agreement, which implies that the future emission budget is limited and we are stepping into the times of emission control. As the most recent study reveals, if we want to prevent the global temperatures from exceeding the 2-degree threshold with a probability higher than 50%, then the cumulative carbon space from 2011 to 2100 ranges from 990 to 1450 G tons of carbon dioxide (GtCO$_2$). Further, if we plan to impose the limit with a higher probability, for example, 66% and 75%, then the corresponding intervals of the emission budget will shrink to [670, 1050] and [610, 830] GtCO$_2$, respectively (Rogelj et al., 2016).

Theoretically, we could obtain the corresponding cumulative emission space for any specific country given the global emission budget under the 2 °C warming-stabilizing goal. The national-level budgets of GHG emissions play a significant role in guiding short-term

emission control activities and the long-term design of emission reduction targets, particularly for China as the largest emitter. Despite the controversy regarding the regional allocation of emission space, there are still certain representative plans that help to allocate the global emission budget across regions in terms of historical emission responsibility and equality. For instance, Raupach et al. (2014) genuinely discuss the allocation of a global cumulative emission budget among the leading economies based on the emission inertia, equality and blended principles. For China, the available emission spaces under the 2-degree warming-rise target are 105.55, 69.55 and 87 G tons of carbon equivalent (GtCeq), which correspond to the three adopted principles. Considering the other two allocation principles, i.e., convergence to equal per capita rights and minimization of the distribution of relative mitigation costs, Tavoni et al. (2015) also estimate the issue of emission allowance allocation. The authors' concluding remarks note that China's available emission budget under the per capita rights convergence rule is equivalent to that under the equality principle given in Raupach et al. (2014). Meanwhile, the estimated emission space in terms of the equal-cost burden-sharing scheme is the lowest, i.e., 60 GtCeq.

Our scenarios design of emission constraints is mainly based on the estimations discussed above. Additionally, we considered one of China's intended nationally determined contributions (INDC) plans that have been dovetailed into the Paris agreement. By employing CE3METL, we determined the critical emission space, i.e., 135.76 GtCeq, for a peak in China's carbon emissions by 2030. On these grounds, we designed 6 scenarios in total, which included a reference scenario and 5 emission control policy scenarios. The details are listed in Table 1. For all the policy cases, CE3METL assumes that an endogenous carbon tax restrains emissions in isolation. Subsidies for alternative technologies are not considered in this work.

4. Result analysis and discussion

Surrounding the designed scenarios, we first examined the long-term evolutionary paths of emissions, and the corresponding policy costs (percentage of GDP relative to the BAU case). Then, we investigated the potential dynamic impacts of climate policies on China's energy security, according to the chosen metrics of energy (oil) intensity, per capita energy (oil) consumption, energy (oil) expenditure and energy diversity.

4.1. Emission trajectories across various restraining scenarios

Consideration of the emissions budgets plays a formidable role in China's future emission paths. Under the BAU case, China may peak its carbon emissions by 2045, and the peak value is to be approximately 3.4 GtC. Thereafter, the emission level is to decline significantly and stabilizes at around 1.23 GtC by the end of this century (Fig. 2). With the intervention of climate policies, carbon emissions will peak in advance, and the corresponding level will decrease remarkably, as the
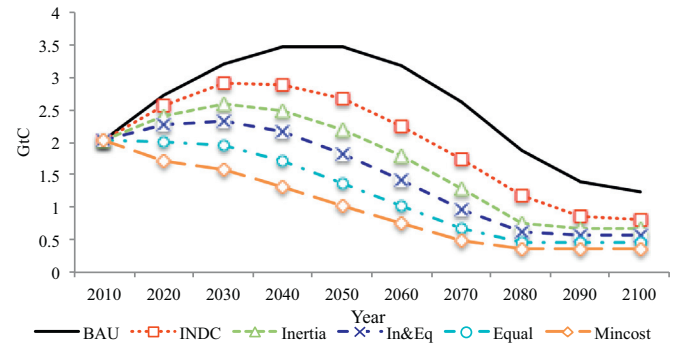

Fig. 2. Evolution of emission paths across various climate policy scenarios.

emission budget shrinks. Specifically, with respect to BAU, the peak year will be advanced to approximately 2030 for all the INDC, Inertia and In&Eq Scenarios, and the relative peak value lowers to 2.89, 2.56 and 2.31 GtC, respectively. For the most stringent emission control scenarios, i.e., Equal, the peak year will be further advanced to 2020, with the peak values to be 2 GtC; while for the Mincost case, the emissions will decrease from the beginning. Thus, whether China could attain its carbon-peaking pledge crucially depends on the available emission budget, i.e., the stringency of the climate policy under the global 2 °C warming-limit target.

4.2. Policy cost analysis

We analyze the costs of climate policies primarily from two aspects: flow costs and stock costs (i.e., cumulative costs). Both are measured by the percentage of GDP relative to BAU. Overall, it is costly to introduce emission budgets and the stricter the emission constraints, the heavier the GDP losses. However, the policy costs may not increase over the entire time. As the climate policy is enhanced, the GDP loss will decrease, and the damaged macro economy will tend to recover. Moreover, the more stringent the climate policy, the earlier the turning point occurs (Fig. 3). Specifically, in the INDC scenario, the policy cost is the lowest when compared to the other policy scenarios, and the flow cost may be lower than 2.4% of the GDP throughout the simulation period. As the emission budget shrinks, the economy will encounter larger damages. For example, in the Inertia scenario, the maximal GDP loss will surpass 5%, which corresponds to the year 2075. When moving to the Equal and Mincost scenarios, the maximal policy costs will further increase to 10.19% and 14.27% of the GDP, with the turning point advanced to 2065 and 2060, respectively. As a rule, the U-shaped paths of GDP loss are primarily caused by the intensive adjustment of the energy structure, which is then driven by the substitution of non-fossil energy for conventional fuels. In the early period of mitigation, low-carbon technologies are mostly immature, and emissions are curbed primarily by reducing the total energy consumption at this stage, which

Table 1
Scenario design and details.

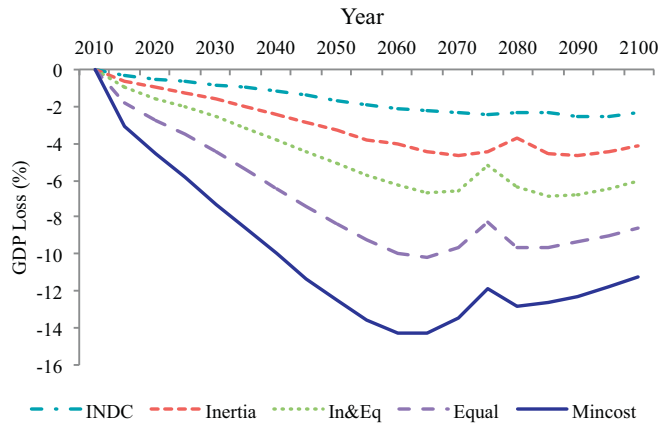| Scenario	Descriptions	Sources
BAU	**B**usiness-**A**s-**U**sual: keeping the current trends of economic growth, energy consumption and technological change, no special climate policies are incorporated.	Optimization of CE3METL
INDC	**INDC**: taking emission constrains into account, and carbon tax policy is endogenously introduced for achieving China's committed carbon-peaking goal in 2030	Optimization of CE3EMTL
Inertia	Emissions **Inertia** (Grandfathering): considering endogenous carbon tax policy, and the available emission budget is estimated by so-called inertia principle under the 2-degree warming threshold	Raupach et al., 2014
In&Eq	Blend of **In**ertia **& Eq**uality: a emission-control case, with the available emission budget estimated in terms of the blended principle of both inertia and equality	Raupach et al., 2014
Equal	**Equal**ity: a emission-control case, with China's cumulative available emission space allocated and determined by the equality principle, given the 2 °C warming-limit goal	Raupach et al., 2014
Mincost	**Min**imizing **Cost** Distribution: a emission-control case, with the cumulative available emission budget allocated by the principle of minimizing distribution of relative mitigation costs	Tavoni et al., 2015

Fig. 3. Flow cost trajectories across various emission-restraining scenarios.

Fig. 5. Evolution of energy (oil) intensity under the given emission budgets
Note: the four dots for all colored lines from right to left correspond to results in
2030, 2040, 2050 and 2070.

directly leads to a larger policy cost. As the incentives resulting from the climate policy are reinforced, non-fossil technologies penetrate well from the cradle to a mature stage, which significantly reduces the dependence of economic growth on GHG emissions and gradually cuts the policy costs down.

The cumulative cost analysis could further verify the above results of flow cost analysis. The growth rate of cumulative costs will remarkably decrease as the considered period lengthens. Meanwhile, the cumulative costs are much lower than flow costs given the same timing nodes across all the policy scenarios. As shown in Fig. 4, the cumulative costs of all the climate policies between 2015 and 2030 fall in the interval of [0.47%, 4.37%]. If the end point is lengthening to 2050, the cost intervals will expand to [0.83%, 7.04%] with the average cost increasing by 3.03% for two decades. For the period of 2015–2070, the corresponding increase of average costs declines to approximately 1.7%. If the entire simulation horizon is considered (i.e., from 2015 to 2100), we would encounter the largest cumulative policy costs, and the cumulative GDP losses in the INDC and Mincost scenarios would be 1.29% and 9.05%, respectively. Thus, regarding the emission budgets given for reaching the global 2-degree warming limit, the macro-economic cost of attaining China's carbon-peaking target should be much lower.

4.3. Impacts of climate policies on energy security

The focus of this section is to explore the potential effects of climate policies on security that are separately measured by energy (oil) intensity, energy (oil) expenditure, per capita energy (oil) consumption and energy diversity.
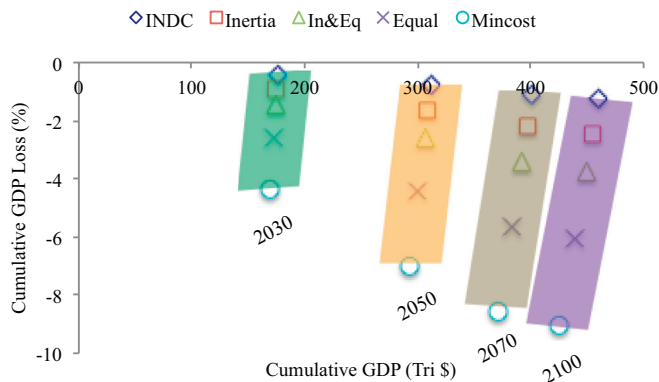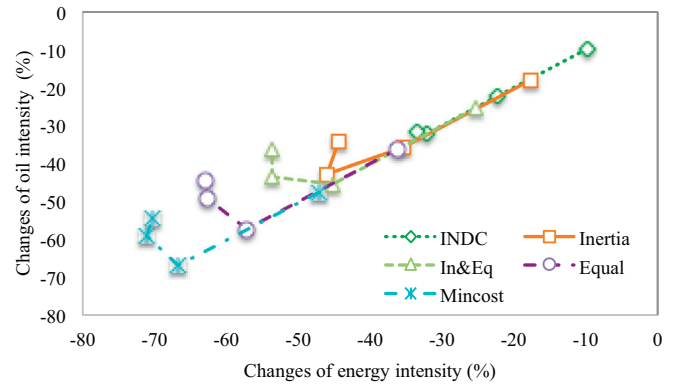

Fig. 4. Distribution of cumulative policy costs given different emission budgets (with a 5% discount rate).

4.3.1. Effects of climate policies on energy efficiency

From the analysis of the evolutionary trends of energy (oil) intensity, we find that: (1) The introduction of emission constraints plays a significant role in the changes of energy (oil) intensity, and the stricter the emission constraints, the lower the energy intensity and the more energy efficiency improves. In 2050, even for the loosest emission control case (INDC), both energy and oil intensity may decrease by approximately 35%, versus over 66% for the most stringent Mincost scenario (Fig. 5). (2) As the climate policies are enhanced, the declining tendency of energy (oil) intensity may slow down, and this is particularly significant for oil intensity.

Per the results under the Inertia scenario, the oil intensity in 2070 will decrease by 45.2% relative to BAU, while in 2100 this value will decline to < 34%, versus only 1.8% for intensity of TPED. A rebound of the decreasing trends of energy (oil) intensity reflects the limited space to improve the energy (oil) efficiency, even under the spur of stringent emission controls. In contrast, the enforcement of climate policies improves the cost competitiveness of non-fossil technologies, which accelerates the substitution of low-carbon energy for conventional fuels, particularly for high carbon-content coal and oil. This effect makes emission reductions no more heavily dependent on decreasing fossil energy consumption, and then the declining rate of oil consumption surpasses the recovery rate of GDP, which is directly responsible for the slowdown of energy efficiency enhancement. Consequently, climate policies help to increase China's security from the perspective of the energy (oil) intensity metric.

4.3.2. Effects of climate policies on per capita energy (oil) consumption

The impacts on energy security using per capita energy (oil) consumptions are portrayed in Fig. 6. Under the BAU case, the per capita energy consumption first increases and then decreases. During the second half of this century, the declining economy growth rate will reduce the demand for energy consumption, and improvements in energy efficiency would intensify this effect. Consequently, the decrease in the growth rate of total energy consumption surpasses that of the population. Overall, the implementation of climate policies plays a negative role in the growth of energy consumption, in spite of the different degrees. This adverse effect will gradually decrease after 2050, which is true for all the emission control scenarios. For example, under the strictest policy case, the per capita energy consumption in 2100 may stabilize at approximately 1 ton of coal equivalent (TCE), and this level is largely in parallel with that in 2070.

Unlike the tendency of energy consumption, under the BAU scenario, the per capita oil consumption steadily decreases from 0.61 TCE in 2030 to 0.48 TCE in 2100 (Fig. 6). Compared to per capita total energy consumption, the influences of climate policies on per capita oil consumption are more remarkable. As time progresses, the per capita
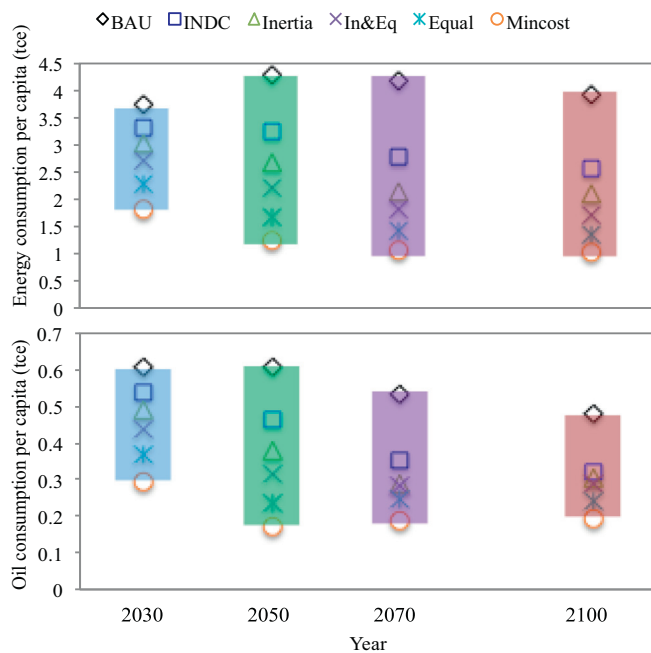
Fig. 6. Changes in per capita energy and oil consumption across various emission budgets.

values across various emission control cases tend to converge, which implies that there is a rebound effect for per capita oil consumption in the late period of emission constraints, particularly for the stricter emission control cases. As a rule, stricter climate policies lead to a larger reduction of carbon-based energy consumption, particularly for the high carbon-content coal. Then, the macro economy growth has to rely more on non-fossil energy, and the lower-carbon-content fuels such as oil and natural gas, also have opportunities to be used as supplementary energy.

The influences of climate policies on per capita energy and oil consumption could be further demonstrated by changes in energy and oil consumption per capita relative to BAU as depicted in Fig. 7. Under the loose scenarios, e.g., INDC, the per capita energy and oil consumption keep declining with the decreases expanding from 10.68% in 2030 to 48% in 2100. When moving to the more compact emission space scenario, the corresponding decreases relative to BAU may significantly shrink during the later period of simulation. In the Mincost scenario, the decrease in oil consumption per capita will shrink from 70.8% in 2050 to approximately 65% in 2100. Consequently, from the perspective of energy and oil consumption per capita, the introduction of emission budgets is beneficial to reduce China's energy system
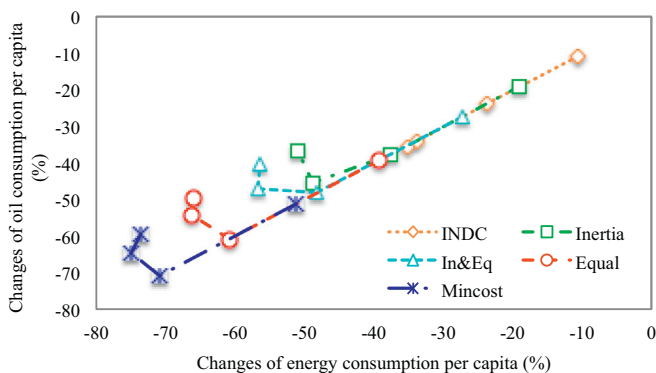
vulnerability, particularly in the short- and medium-term.

4.3.3. Effects of climate policies on energy (oil) expenditures

Energy expenditures, particularly oil expenditures, provide another critical view for examining security. Fig. 8 demonstrates that energy and oil expenditures steadily increase under the BAU case, from 2.44 and 0.56 trillion US dollars (USD) in 2030 to 5.65 and 2.15 trillion USD in 2100, respectively. Meanwhile, in the presence of emission budgets, both energy and oil expenditures will decrease with respect to BAU, and the degree of the decline is greatly consistent with the stringency of the climate policies. For example, in the INDC scenario, energy and oil expenditures in 2100 will reduce to 3.76 and 1.43 trillion USD, respectively, versus 2.03 and 1.01 trillion USD in the strictest Mincost scenario.

The conclusions drawn above could be better verified and comprehended by the relationships shown in Fig. 9. The decrease in trends of energy and oil expenditures in all the policy scenarios is consistently prominent relative to BAU. In the INDC scenario, the maximum decrease reaches 47.9% and 48% for energy and oil expenditures, respectively, versus 70.7% and 70.8% in the strictest Mincost scenario. As

Fig. 8. Changes in energy and oil expenditures given different emission budgets.

Fig. 7. Relationships between changes in per capita energy consumption and oil consumption.

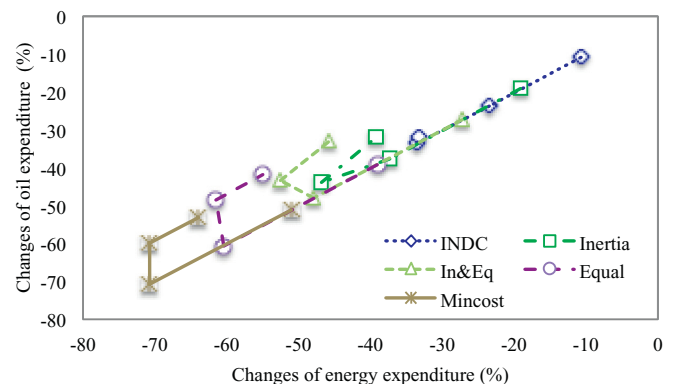**Fig. 9.** Relationships between changes in energy and oil expenditures relative to BAU.

the emission control activities deepen, the decreasing trends in both energy and oil expenditures slow remarkably. For example, both energy and oil expenditures decrease by approximately 61% in 2050 in the In& Eq scenario, while this value rebounds to 45.69% in 2070 and 33% in 2100, respectively. When turning to the Mincost scenario, the decrease in energy and oil expenditures relative to BAU in 2100 will be 6.66% and 17.9% lower than those in 2050. From the analysis of energy and oil expenditure metrics, we conclude that the implementation of climate policies helps to improve China's situation of security.

4.3.4. Effects of climate policies on energy diversity

As discussed in Section 2, both SWDI and HHI are representative metrics for measuring energy diversity, which is an important signal in determining the degree of security in an energy system. Owing to the results equivalency between SWDI and HHI (Grubb et al., 2006; Kruyt et al., 2009), the emphasis of this section is on exploring the impacts of emission controls on SWDI-based energy diversity.

Note: the embedded subfigure provides the relative changes of SWDI (relative to BAU).

Fig. 10 shows that the SWDI path under the BAU scenario steadily increases until 2080, and then, begins to decrease. This trend implies that China's energy diversity will steadily improve for quite a long time, during which both conventional fuels and alternatives would coexist. The successive increase in energy system diversity primarily stems from the rapid deployment of non-fossil technologies. When stepping into the second half of this century, the decreasing potential of traditional fuels in the energy market gradually becomes limited. Additionally, the growth of non-fossil energy tends to stabilize relatively, which largely explains the declining trend of the SWDI path. In the short- and medium-term, the implementation of climate policies helps to increase energy diversity, particularly for the more stringent policies. In the long-run, the trajectories of SWDI follow a hump shape, i.e., the values of SWDI keep increasing until they arrive at inflection points, and then the values decline; the stricter the climate policies, the earlier the inflection points appear. In fact, these national-level results are consistent with the relative results at the global scale (Cherp et al., 2016). For example, the appearance of an inflection point will be advanced from 2080 under the BAU scenario to approximately 2070 in the INDC scenario, and the corresponding SWDI value increases 10% in the BAU level. In the Mincost scenario, the turning point of the SWDI path will appear in 2045, and the increase of the SWDI value reaches 33% in comparison to that in the BAU scenario (Fig. 10).

As a result of climate policies, total emissions are largely reduced. The reduction is achieved primarily by curbing total conventional energy consumption, particularly when the majority of the non-fossil technologies are at their nascent stage. Again, the stricter the climate

policies, the more fossil energy consumption will be reduced, which to a large extent, explains the movement of inflection points discussed above. Regardless, the deployment of non-fossil technologies itself heavily relies on the effects of the climate policies. In general, a stricter climate policy (e.g., carbon tax) directly increases the use cost of fossil fuels, and this cost increase is equivalent to improving the cost competitiveness of non-fossil technologies and promoting their market penetration. Consequently, climate policies are effective for increasing China's energy security in the short- and medium-term, according to the metric of energy diversity.

5. Discussions and conclusions

The intention of this work was to develop a well-formed framework of 3E-integrated systems to examine the potential effect of China's climate policies on security, with a particular focusing on the dynamic, long-term effects of emission budgets on energy security. Climate policies in this paper mainly refer to the endogenous carbon taxes under given emission budgets, and energy security is measured by the metrics of energy (oil) intensity, energy (oil) expenditures, per capita energy (oil) consumption and SWDI-based energy diversity.

The analyses that assess the energy (oil) intensity and energy (oil) expenditures support the finding that implementation of emission control policies yields the prominent co-benefits of security, regardless of whether looking at the short-, medium- or long-term. As observed from the perspective of per capita energy (oil) consumption, the introduction of emission budgets promotes the decrease in both per capita energy and oil consumption. These outcomes translate to an increase in the energy system security to a large extent. However, this effect is sensitive to the time scale of climate policies when compared to the long-term, the short- and medium-term influences of the climate policies on per capita energy and oil consumption seem more remarkable. For the metric of energy diversity, the co-benefits of security that result from emission budgets are also closely related to the considered time scales. Specifically, the implementation of emission control policies significantly increases China's energy diversity in the short- and medium-term before 2050. Afterward, the energy diversity will decrease until it is lower than the BAU level, at which point, the energy system may become more vulnerable than in the no emission budget cases.

In closing, climate policies in China contribute to avoiding potential climate damages, and bring the numerous co-benefits of energy security, particularly in the short- and medium-term. More specifically, the macroeconomic costs required to reach China's committed carbon-peaking target in 2030 are estimated to be far lower than the costs required to fulfill the emission budgets under the global 2-degree warming rise threshold, which implies that the economics of climate policy is expected to significantly improve, if the co-benefits of energy security are well taken into account. This finding provides new reasonable support for introducing climate policies at the national level. In effect, the unidirectional consistency between climate policies and energy security has been found from a global perspective (Cherp et al., 2016; Jewell et al., 2016), however, this consistency is worthy of scrutiny. Climate change always performs as a public issue on the global scale, while energy security is more like a private problem at the national level, which may contradict with each other. For example, restraining the use of conventional fuels is one of main objectives of most climate policies, this is likely to aggravate the imbalance and inequality of energy use among different regions, then damage the energy security of developing countries. When it comes to the national scale, both climate change and energy security are reduced to pure private problems, and the unidirectional consistency we have found in this work is therefore more dependable and reasonable. Thus, we suggest the enforcement of regional climate policies, not only for copping with global warming risks that are still full of doubts, but for urgent and severe situation of regional energy security.
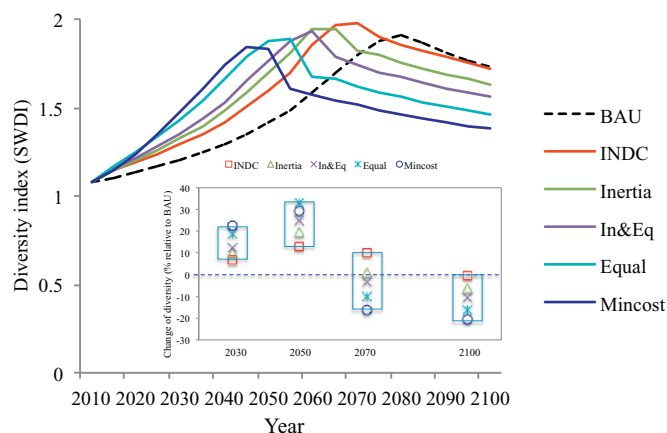

Fig. 10. Dynamic paths of SWDI-based energy system diversity across various policy scenarios.

Certainly, the results obtained in this paper may also be affected by certain factors that have not been covered: first, energy trades, particularly for oil trades, have been proven to be an important indicator in measuring energy security. However, because of the assumption on closure conditions in a national model, we did not take energy or oil trades into account. Notwithstanding, the energy (oil) trades have been widely considered as one of metrics with which to assess energy security in global IAMs, and the relative results support the finding that climate policies positively improve energy security (Jewell et al., 2014, 2016). Second, CE3METL does not cover non-conventional fuels such as shale oil and shale gas, or low-carbon technologies and negative emission technologies, such as carbon capture and storage (CCS) and bio-energy with CCS (BECCS), which may overestimate the energy system vulnerability as measured by energy diversity (Cherp et al., 2016). Finally, we currently fail in measuring the diversities of power system and transportation system, which are proven to be key constituents of vital energy systems (Grubb et al., 2006), owing to the modeling limitation of this single-sector 3E framework. As a rule, the diversity of energy systems will increase with the enriching of technological details. Therefore, the absence of all the factors mentioned above should not change our primary findings. On the contrary, further consideration of these factors may improve and reinforce our conclusions.

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